UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Potential of a New Generation of Two-Stroke Engines for Powertrain Electrification

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Motivations

The new generation of 2-stroke engines can be an ideal match for electric motors in many hybrid applications, such as:

- Range extenders running on gasoline/ethanol for small electric vehicles, aircraft, boats
- hybrid passenger cars, commercial vehicles, off-road vehicles, boats, trucks, running on Diesel (or similar fuels)/Natural gas/dual fuel
- hybrid high performance motorcycles running on gasoline or ethanol

Advantages in comparison to conventional 4-strokes:

1) Compactness and weight and cost, compensating the additional charge imposed by hybridization
2) Better capability to operate at clean and efficient combustion modes (HCCI, CAI, jet ignition, …)
3) Better fuel efficiency and NVH in most cases

Main concerns to be addressed (in general):

- Reliability
- Lubricant consumption

Presentation outlines

- A successful two-stroke engine concept
- Two-Stroke engines for hybrid marine powerplants
- A two stroke range extender
- Other 2-stroke projects at UNIMORE

The Opposed Piston concept by Achates Power

EFFICIENCY OVERVIEW

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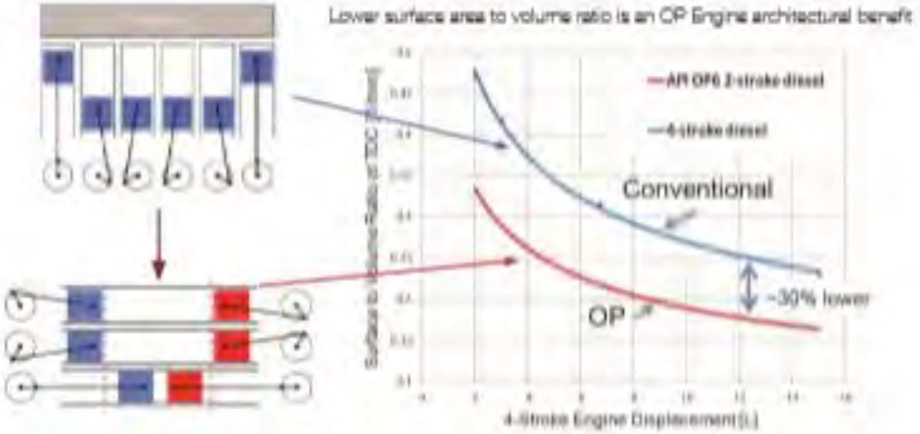
Reduced Heat Losses

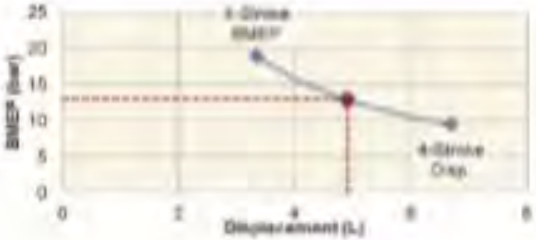
Lower surface area to volume ratio is an OP Engine architectural benefit



The OP Engine benefits from lower surface area to volume ratio, longer stroke to bore ratio, and larger volume per cylinder.

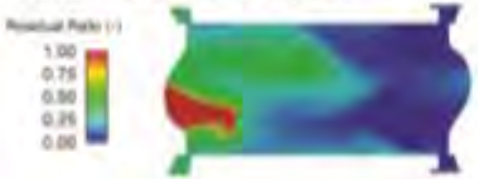
ENGINE	4 STROKE	OP ENGINE
Power Output Range	6	3
Trapped Volume/Cylinder	1.0L	1.6L
Stroke/Bore Ratio	1.1	2.2
Trapped Compression Ratio	15:1	15:1
Combustion Chamber Surface Area/Volume (mm⁻¹)	0.28	0.18

The opposed piston architecture enables a smaller displacement and lower BMEP operation compared to four stroke engines. The lower BMEP results in lower heat transfer losses, higher efficiency, as well as lower NOx emissions.

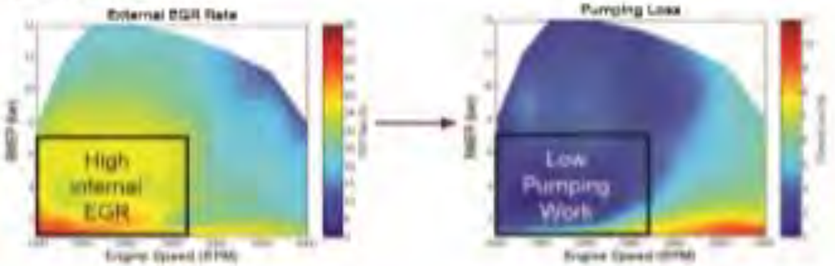


Lower Pumping Losses

Compared to pumping exhaust out of the cylinder with a piston, an OP engine breathes via pressure differential across the intake and exhaust ports. This allows for low-pumping control of internal EGR as well as flexible induction of external EGR.



Under part load conditions, an OP Engine's efficiency is enhanced through internal EGR and very low pumping losses.



EFFICIENCY OVERVIEW

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More Optimal Combustion

The rate of heat release, as given by the first law of thermodynamics, is dependent on the ratio of specific heats (γ) of the gas mixture, pressure (p), and volume (V). For the same max pressure rise rate, the larger cylinder volume of the OP Engine leads to faster combustion.

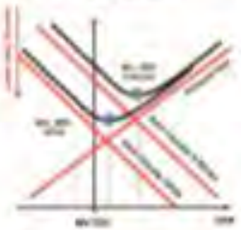
1st Law of Thermodynamics

4S Engine

$$\frac{dQ_{[illegible]}}{d\theta} = \frac{\gamma}{\gamma-1}p\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\boxed{\frac{dp}{d\theta}} = \text{same}$$

OP2S Engine

$$\frac{dQ_{[illegible]}}{d\theta} = \frac{\gamma}{\gamma-1}p\frac{d([illegible]V)}{d\theta} + \frac{1}{\gamma-1}([illegible]V)\boxed{\frac{dp}{d\theta}}$$



The reduced heat transfer losses of the OP Engine lead to a more advanced and optimally phased combustion event compared to a conventional four stroke engine. This in turn allows a significantly higher rate of heat release for the same max pressure rise rate.

SNAPSHOT: ADVANCED COMBAT ENGINE

OP Engines are ideally suited to applications that demand superior fuel efficiency, low heat rejection and compact thermal management.

Significant advantages over incumbent:

- HP from 675 to 1000
- Increased ISG Capability
- Cooling Pack Reduction
- After Filter Reduction

SPECIFICATION	INITIAL PROGRAM	SUBSEQUENT PROGRAM
Power Output Range	200 - 300 hp (149 - 224 kW)	750 - 1500 hp (560 - 1120 kW)
Specific Power	>=70 hp/L (52.2 kW/L)	70 hp/L
Brake Specific Fuel Consumption	<=219 g/kWh	195 g/kWh
Heat Rejection	≤0.71 kW/kW	0.45 kW/kW
Durability Requirements	50 hr NATO	50 hr NATO + 400 hr NATO

Test Engine & Empirical Results

The A48 engine has been Achates Power's principal test bed with over 12,000 hours of test cell development time logged.

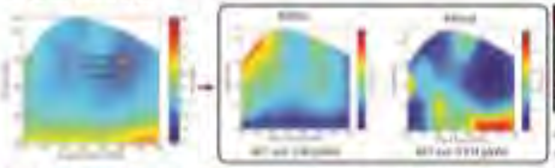
- Displacement 4.9L
- Bore: 98 mm
- Stroke/Bore 2.2
- Turbo GTX2860
- Supercharger: R1320
- SC driven by intake crank
- Geartrain: 5 gears
- Fuel, oil and water pumps are engine driven
- Fuel pump: Bosch CP4
- Injectors: Bosch and Denso

Research Engine

Production Engine

- 275 hp rated power @2200 rpm
- 275 hp 811 lb.-ft. peak torque @ 1200 - 1600 rpm
- Engine out emissions compatible with US EPA 2010 assuming DOC, DPF, SCR

STEADY STATE



12 MODE SET CYCLE RESULTS		
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[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

High efficiency in broad load speed range - 42.6% BTE

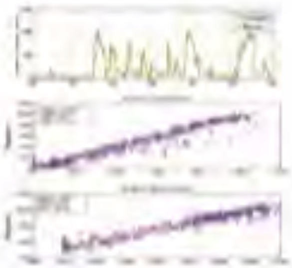
21% improved efficiency over conventional four-stroke engines

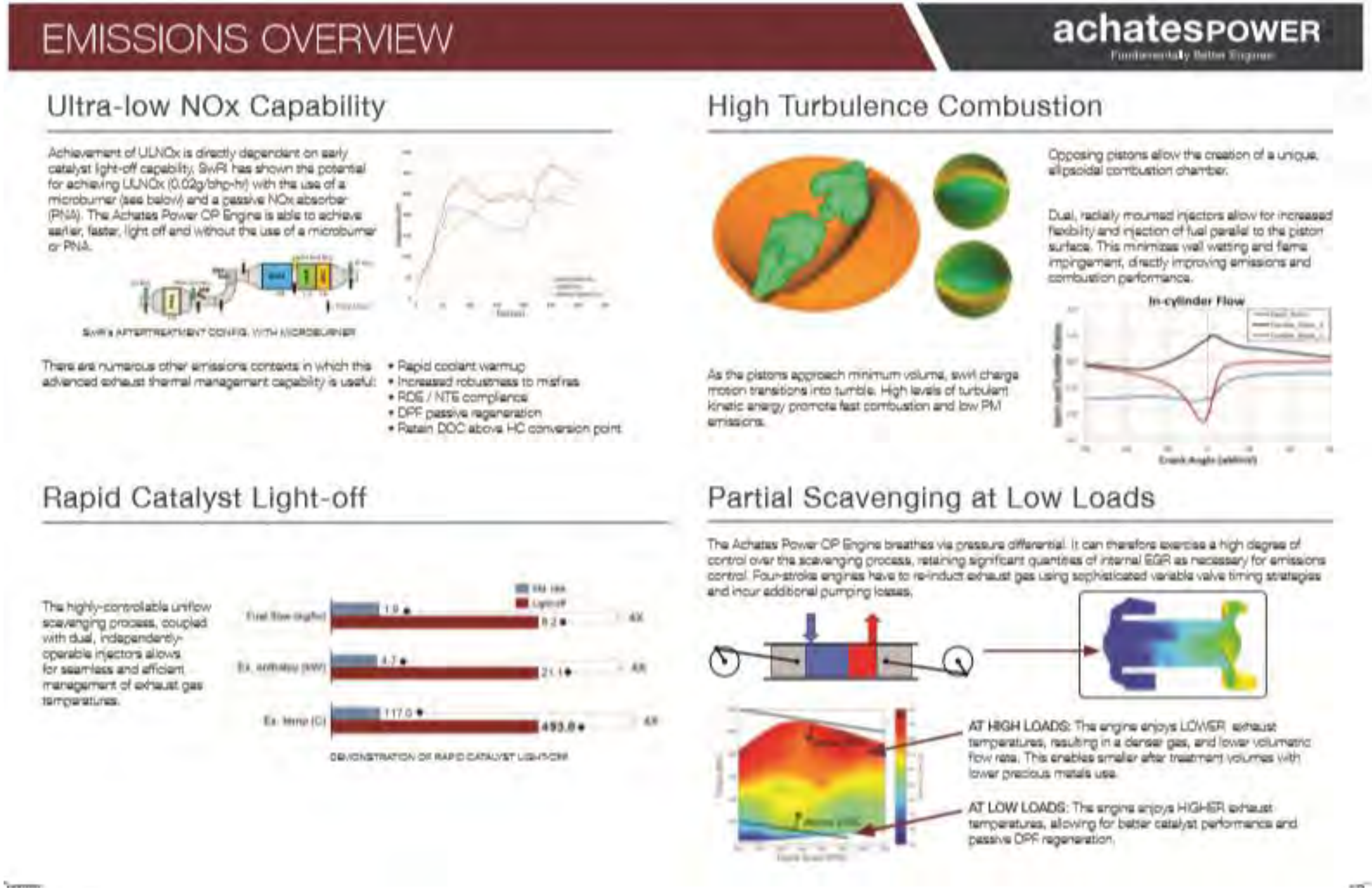
30% better than comparable four-stroke engines

A fully optimized 5L OP engine will have cycle (SET) average BTE of 46.6%.

HEAVY DUTY HOT FTP TRANSIENT

	[illegible]	[illegible]
Total Energy Generated Over The Cycle (kWh)	14.75	15.30
Total Fuel Consumed (kg)	3.30	4.00
BSFC (g/kWh)	217.3	261.4
Brake Th. Eff (%)	38.x	31.8





EMISSIONS OVERVIEW

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Ultra-low NOx Capability

Achievement of ULNOx is directly dependent on early catalyst light-off capability. SwRI has shown the potential for achieving ULNOx (0.02g/bhp-hr) with the use of a microburner (see below) and a passive NOx absorber (PNA). The Achates Power OP Engine is able to achieve earlier, faster, light off and without the use of a microburner or PNA.

SwRI's AFTERTREATMENT CONFIG. WITH MICROBURNER

There are numerous other emissions contexts in which this advanced exhaust thermal management capability is useful:

- Rapid coolant warmup
- Increased robustness to misfires
- RDE / NTE compliance
- DPF passive regeneration
- Retain DOC above HC conversion point

High Turbulence Combustion

Opposing pistons allow the creation of a unique, ellipsoidal combustion chamber.

Dual, radially mounted injectors allow for increased flexibility and injection of fuel parallel to the piston surface. This minimizes wall wetting and flame impingement, directly improving emissions and combustion performance.

In-cylinder Flow

As the pistons approach minimum volume, swirl charge motion transitions into tumble. High levels of turbulent kinetic energy promote fast combustion and low PM emissions.

Rapid Catalyst Light-off

The highly-controllable uniflow scavenging process, coupled with dual, independently-operable injectors allows for seamless and efficient management of exhaust gas temperatures.

1.9
8.2
4X
4.7
21.1
4X
117.0
493.8
4X

DEMONSTRATION OF RAPID CATALYST LIGHT-OFF

Partial Scavenging at Low Loads

The Achates Power OP Engine breathes via pressure differential. It can therefore exercise a high degree of control over the scavenging process, retaining significant quantities of internal EGR as necessary for emissions control. Four-stroke engines have to re-induct exhaust gas using sophisticated variable valve timing strategies and incur additional pumping losses.

AT HIGH LOADS: The engine enjoys LOWER exhaust temperatures, resulting in a denser gas, and lower volumetric flow rate. This enables smaller after treatment volumes with lower precious metals use.

AT LOW LOADS: The engine enjoys HIGHER exhaust temperatures, allowing for better catalyst performance and passive DPF regeneration.

2-Stroke Diesel Engines for hybrid boats
(in cooperation with GM)

Mattarelli, E., Rinaldini, C.A., Savioli, T., Warey, A. et al., “An Innovative Hybrid Powertrain for Small and Medium Boats,”
SAE Technical Paper 2018-01-0373, 2018, doi:10.4271/2018-01-0373

Why hybrid boats? Why 2-stroke?

Highly desirable to sail into harbors, channels, lagoons, et cetera without ICEs

Drawbacks of a full electric propulsion system: 1) cost and weight of the battery pack, 2) concerns for safety

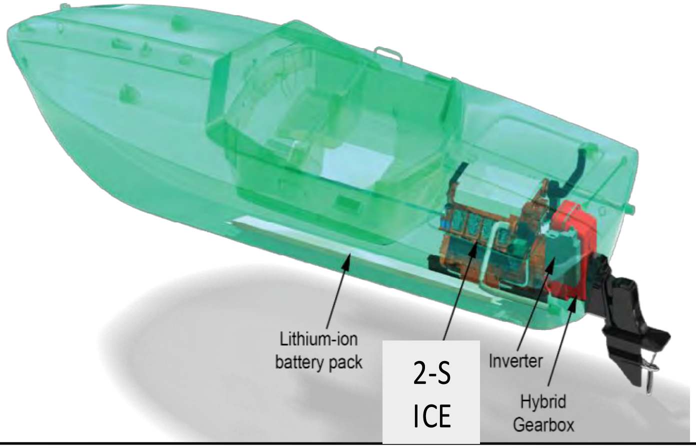
Hybrid powertrains (ICE+EM)

PRO: reduced weight and cost of batteries (vs full electric); zero-emissions on short trips, assistance of the EM →Power derating →less expensive ATS

CONS: increase of complexity, overall dimensions, weight and costs of the powertrain

New approach to the design of ICEs, in order to exploit the synergies and minimize the related drawbacks

Modern 2-Stroke Compression Ignition (Diesel) engines are not only more compact and light than 4-strokes, they can be also more efficient, and clean



High-Speed 2-Stroke Diesel engines

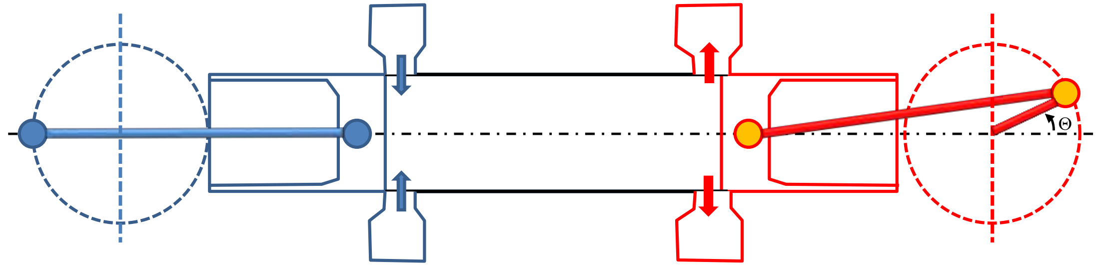
- ✓ Downsizing/down-speeding potential
- ✓ Soot/NOx emissions benefits at part load conditions (↑AFR, internal EGR)
- ✓ Engine hardware: lower complexity and cost

•In the most widespread design, exhaust poppet valves are adopted, but…

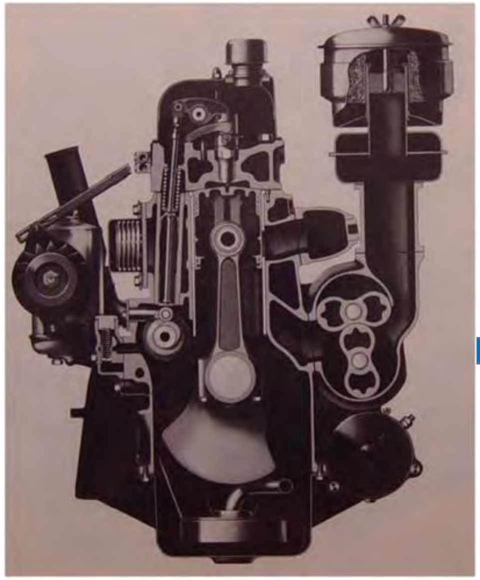
•No poppet valves:

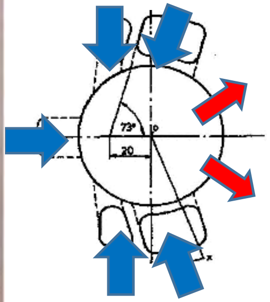
1) Opposed Piston (OP)
2) Loop Scavenging (LS)

Opposed Piston design



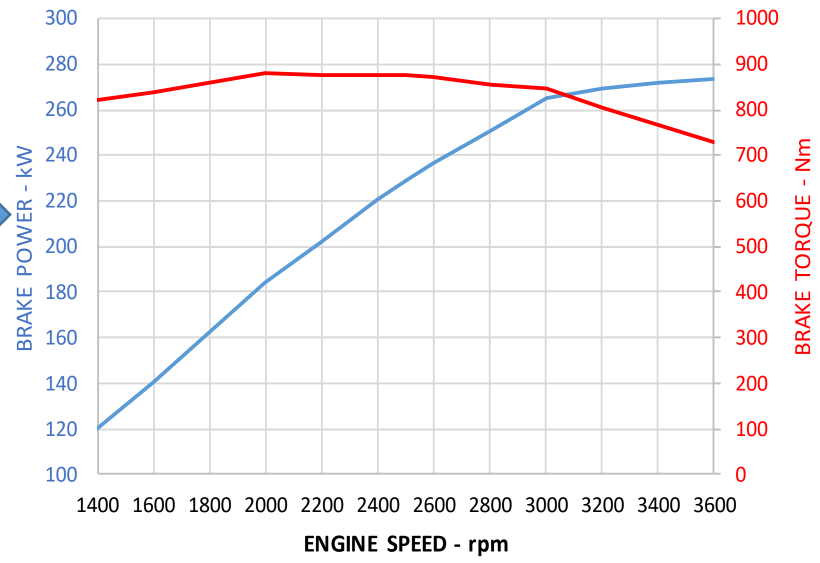
Loop design

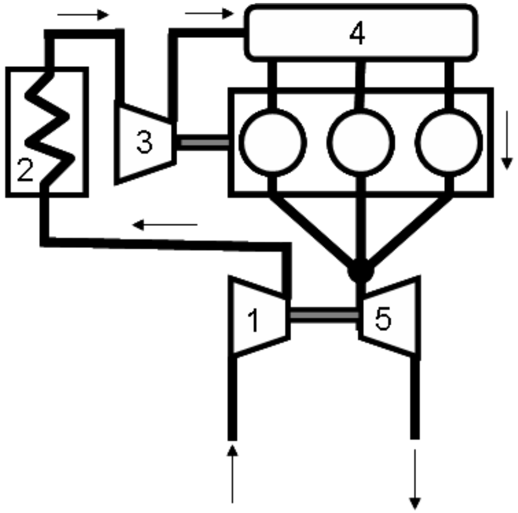




Project goals and constraints

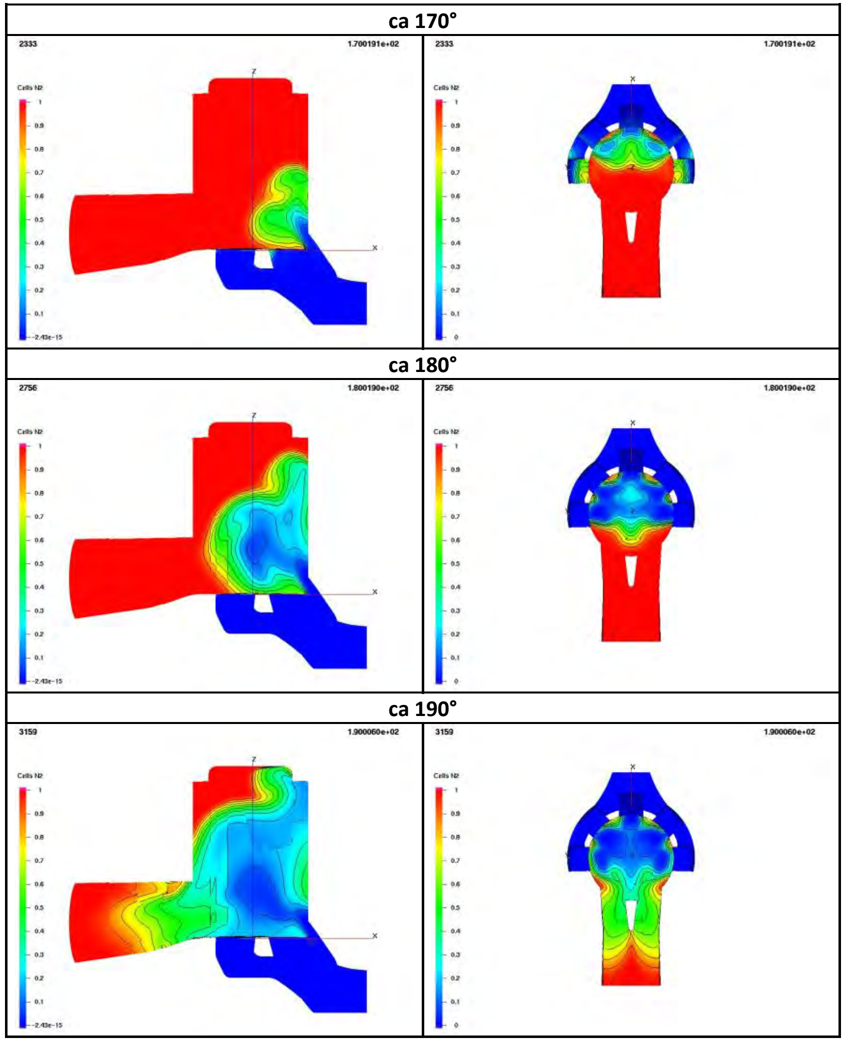
- 2-Stroke configurations selected: loop scavenged (LS) and opposed piston (OP)
- Reference 4-Stroke engine: Volvo Penta D6 370A, L6 5.5 liter, maximum power: 272 kW @3500 rpm, maximum torque 880 Nm@2000rpm, dry weight: 580 kg
- GOAL: replace the conventional 4S engine with a full hybrid powertrain (battery pack included), same performance without increasing overall weight and dimensions
- Main constraints: 1) peak combustion pressure: 160 bar; 2) same or higher AFR of the 4-S engine; 3) max. turbine inlet temperature: 850 °C; 4) Turbine back-Pressure at max power: 1.4 bar…..
- Engine Layout: VGT turbocharger (1,5), intercooler (2), supercharger with electronically controlled by-pass (3), optimized intake and exhaust manifolds (4)

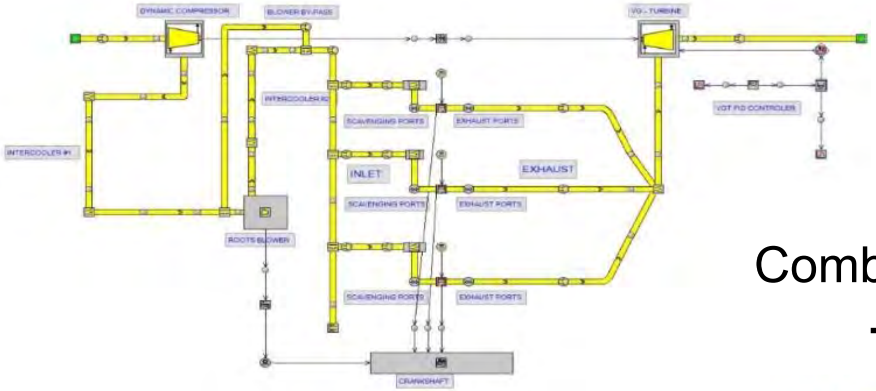


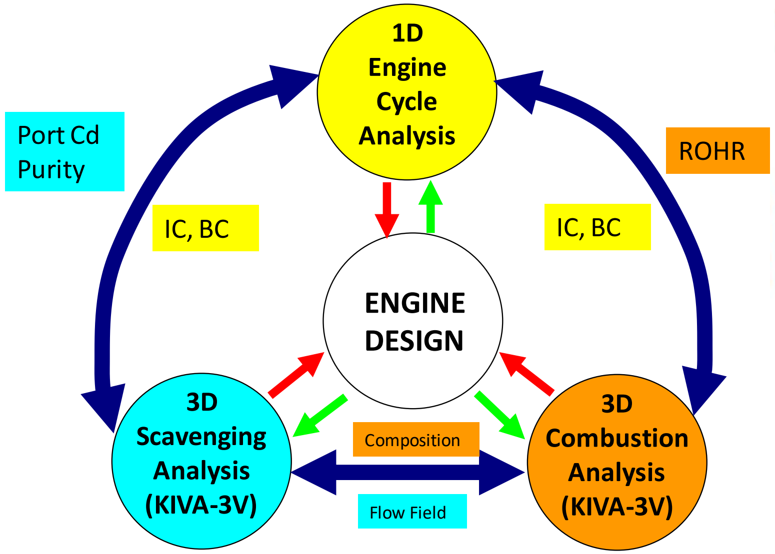


Engine design based on CFD 1D and 3D simulations

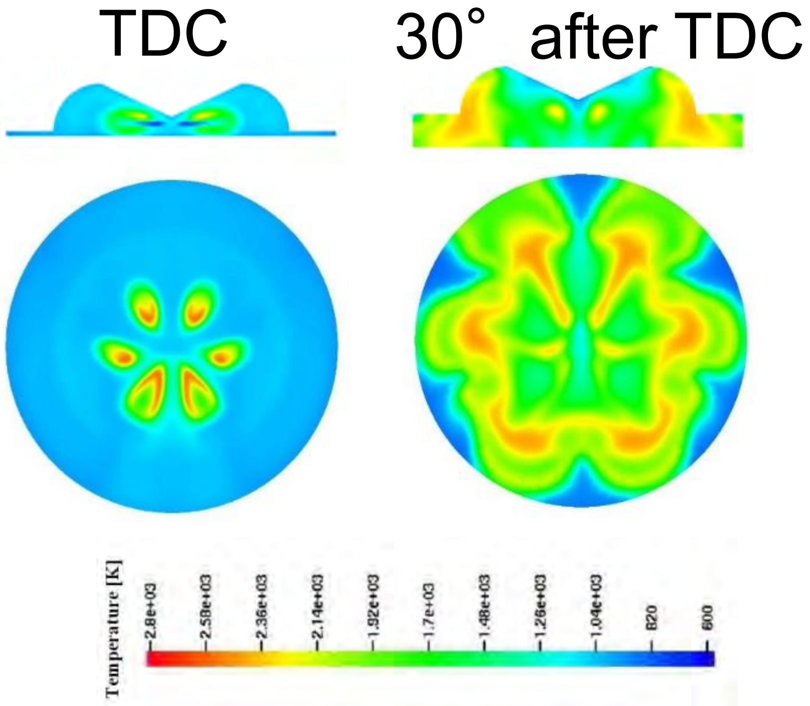
Scavenging analysis on the LS engine





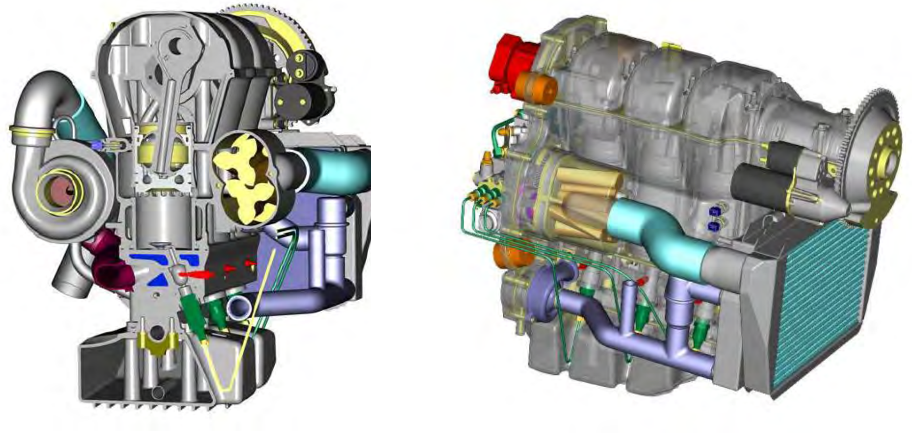


Combustion analysis on the LS engine



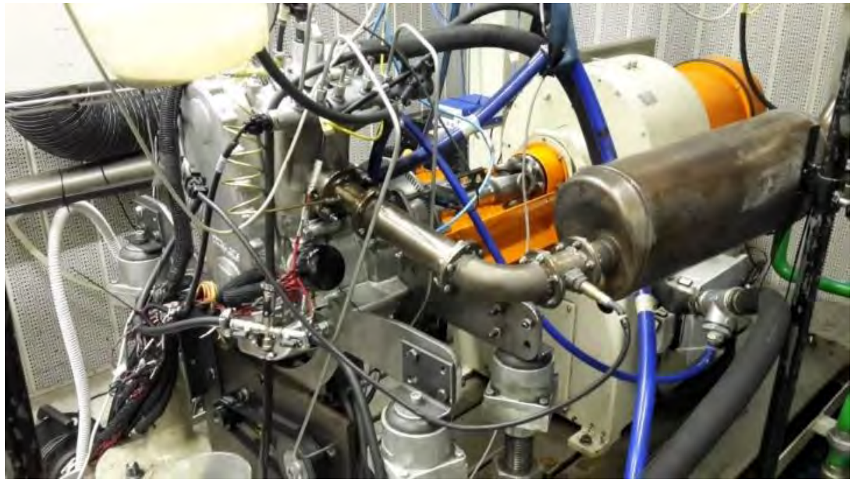
CFD simulation supported by experiments

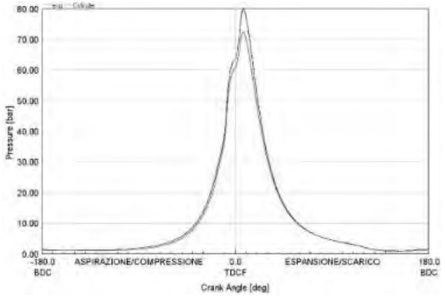
WAM aircraft engine

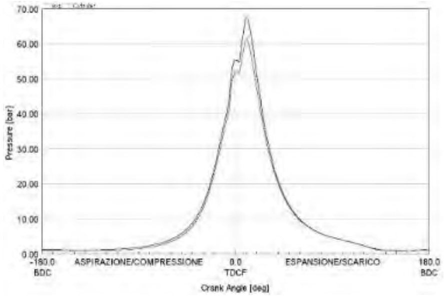


Engine type	2-Stroke, 3-cylinder in-line
Combustion	Diesel, Indirect Injection
Scavenging type	Uniflow
Number of Valves/Ports	2 Exh. valves/20 inlet ports
Air Metering	Turbocharger + Roots
Fuel Metering	In-line mechanical pump
Injector nozzle type	Single-hole (Pintle)
Displaced volume	1832 cc
Stroke	90.5 mm
Bore	95.0 mm
Connecting Rod	167.0 mm
Compression ratio	17:1
Exhaust Valves Open	83° BBDC
Exhaust Valves Close	80° ABDC
Inlet Port Open	53° BBDC
Inlet Port Close	53° ABDC
Maximum Brake Power	100/120 HP @ 2750 rpm

Single-cylinder, 0.5L, loop scavenged HSDI prototype





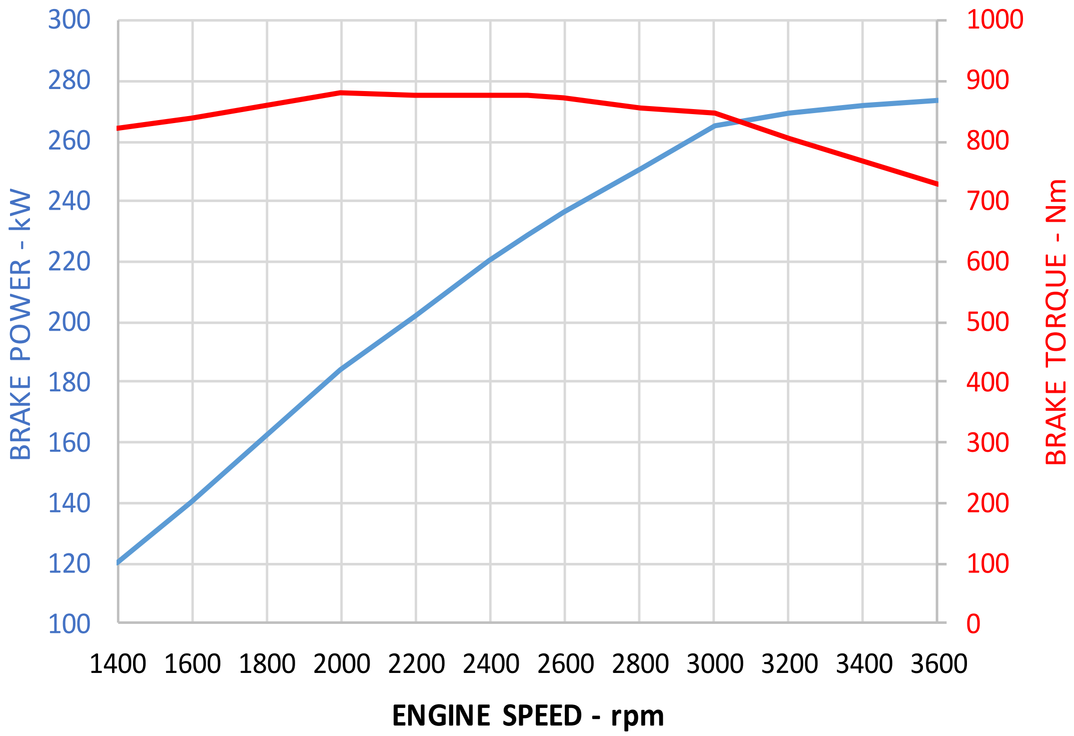


N	Lambda	IMEP	CO2	NOx	CO	HC	CO2	NOx	CO	HC
rpm		bar	%	ppm	%	ppm	g/kWh_i	g/kWh_i	g/kWh_i	g/kWh_i
1833	2.46	6.35	5.2	421	0.02	47	556	3.07	1.36	0.82
1535	2.78	6.33	4.3	616	0.01	15	531	5.17	0.78	0.30
1160	3.09	6.29	3.9	443	0.01	15	567	4.39	0.92	0.36
1822	4.56	3.81	3.1	244	0.05	23	563	3.02	5.78	0.68
1524	5.03	3.68	2.6	214	0.04	12	550	3.09	5.39	0.42
1160	5.43	3.67	2.5	135	0.04	12	614	2.28	6.30	0.49

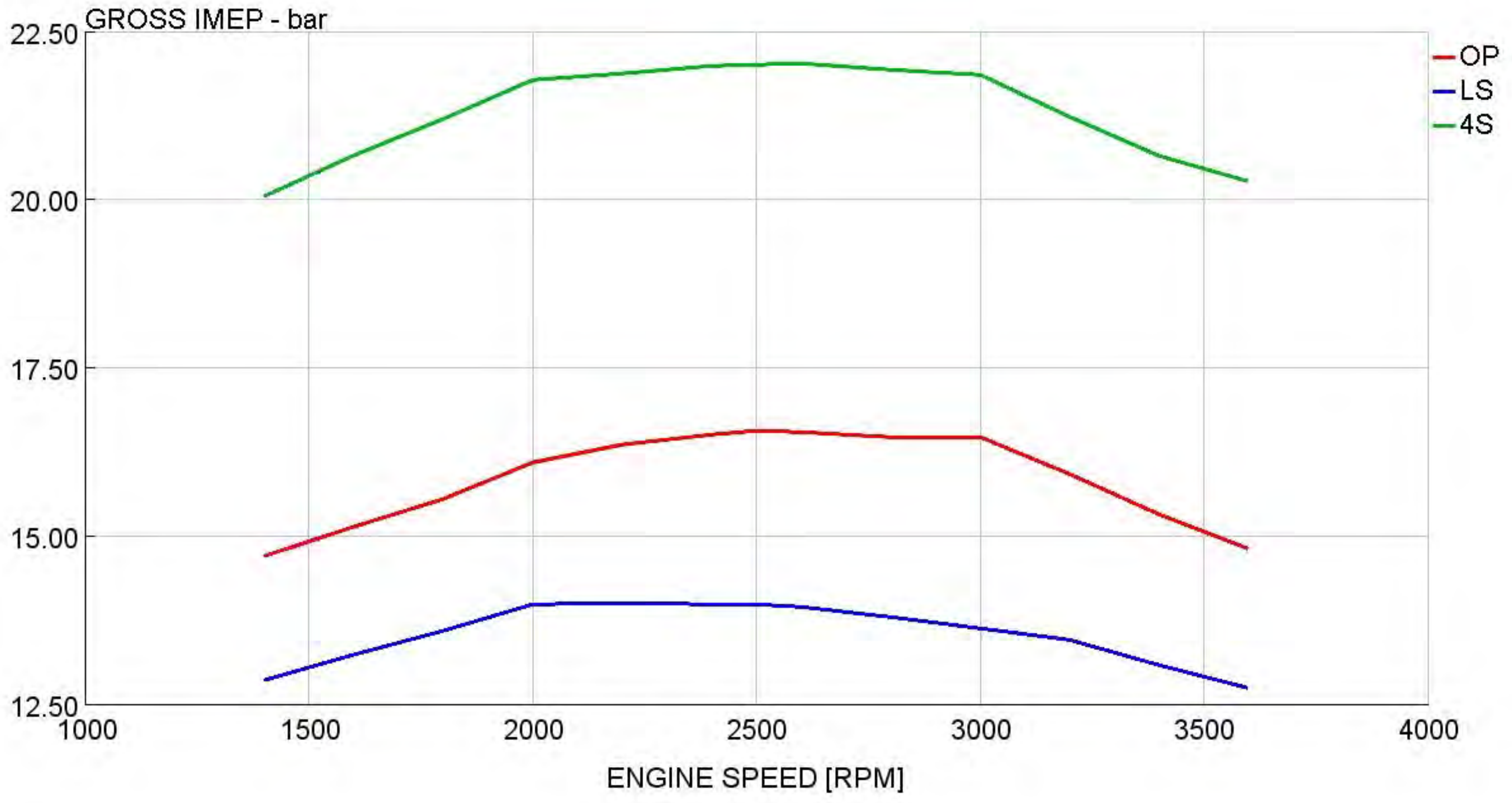
SAE P. #2018-01-0373

Final main features of the 2-S engines

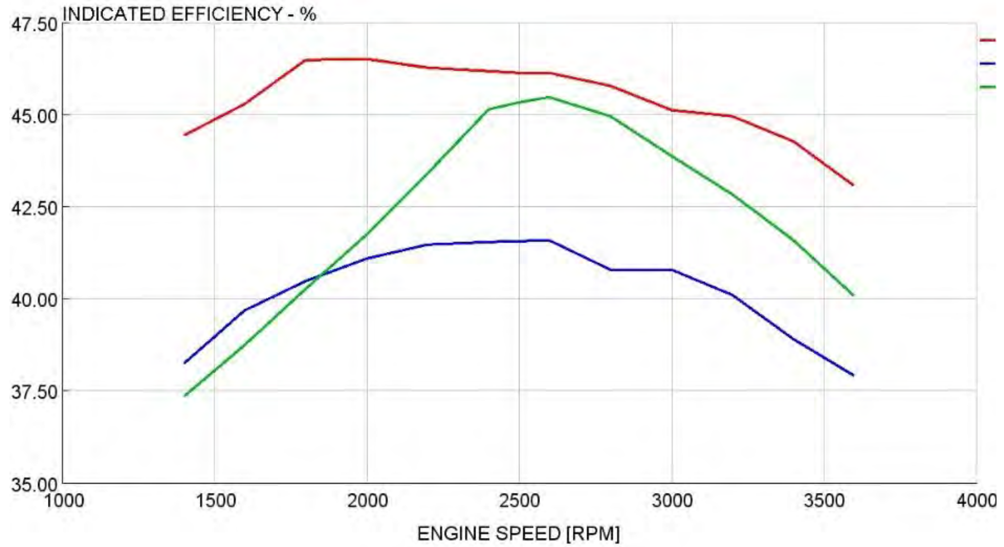
	Unit	LOOP	OP
Bore	mm	94	84.3
Stroke	mm	100	109.5
Connecting rod length	mm	200	222.5
Compression Ratio	-	18	18
Max. Engine Speed	rpm	3600	3600
Max. Mean Piston Speed	m/s	12	13.14
Number of cylinders/pistons	-	6/6 (V120)	3/6
Unit Displacement (per piston)	cc	694.0	610.9
Total Displacement	cc	4164	3665

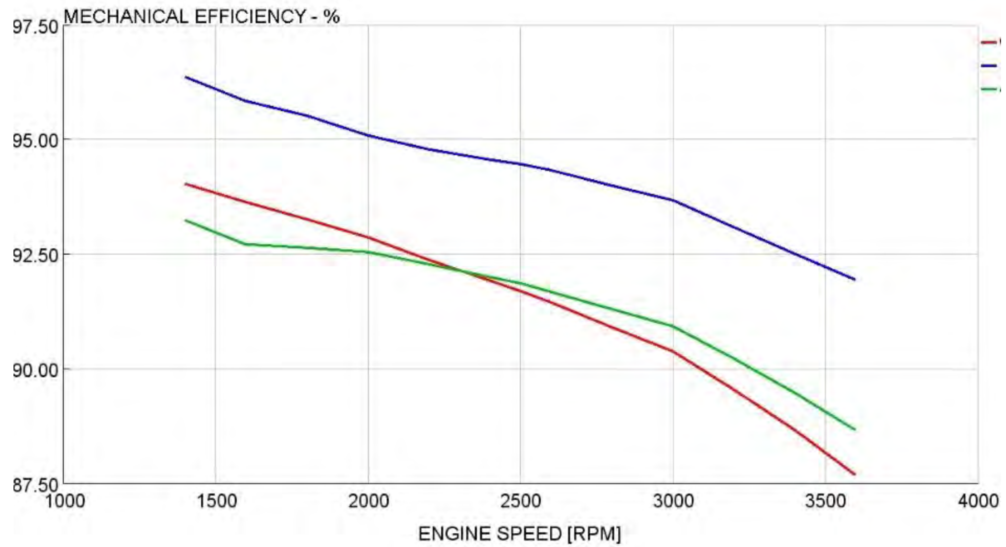


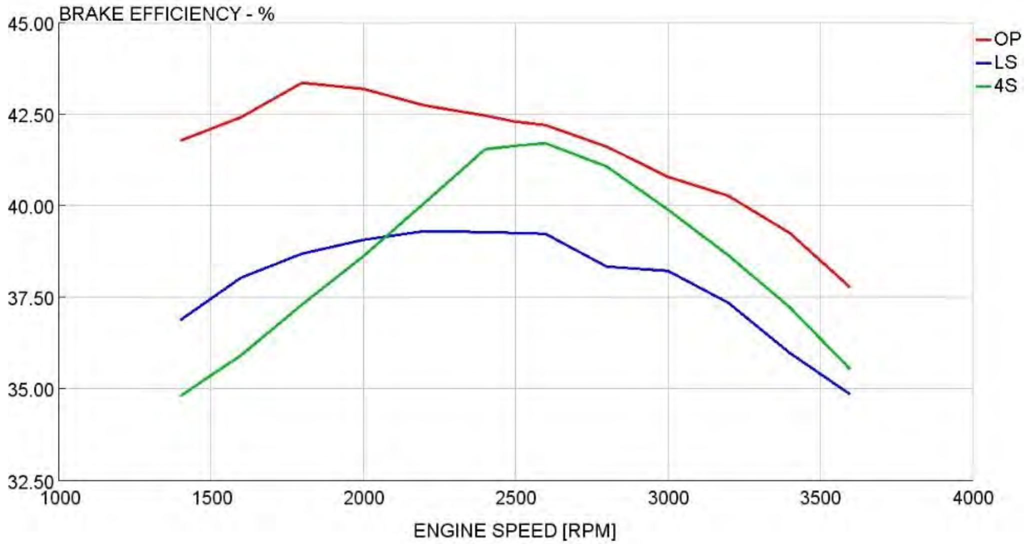
Comparison at full load: IMEP



Comparison at full load: efficiencies



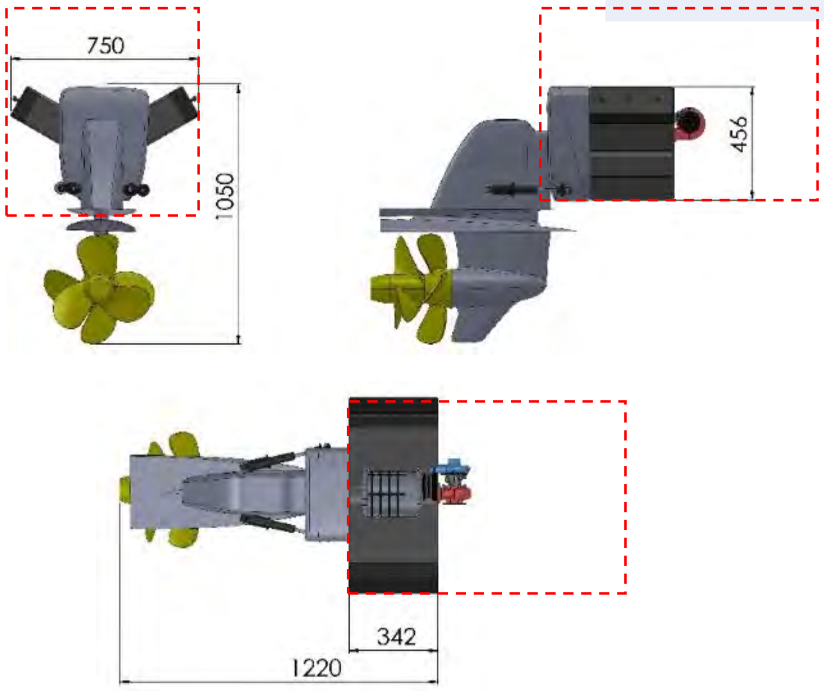




Overall dimensions

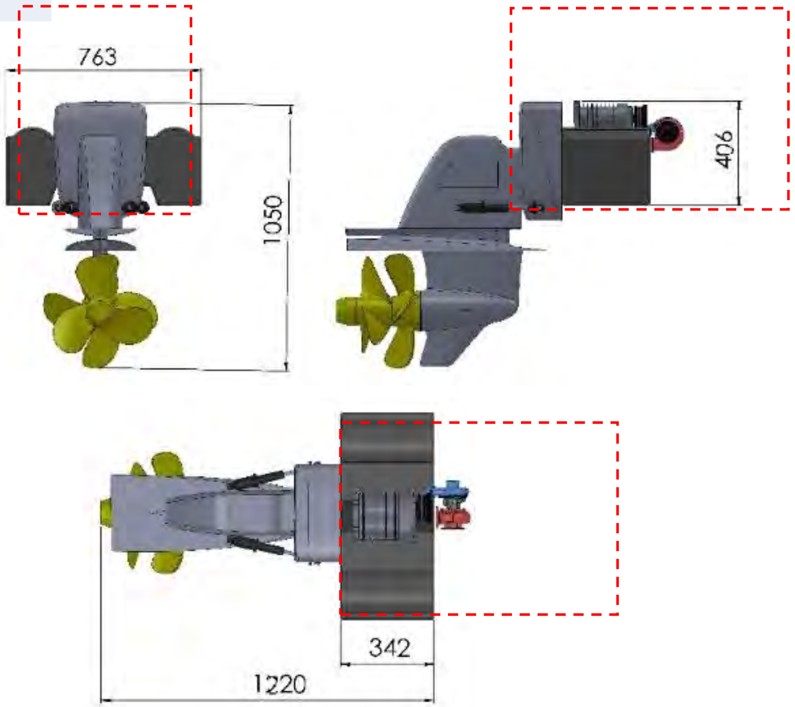
	4S	LS	OP
Engine length (crankshaft axis) - mm	1020	342	342
Engine width - mm	754	750	763
Engine height - mm	780	456	406
Overall engine volume - liter	600	117	106

Loop Scavenged



4S engine dimensions

Opposed Piston

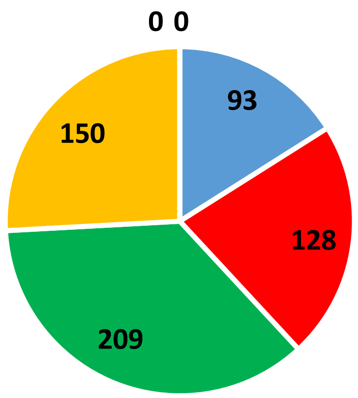


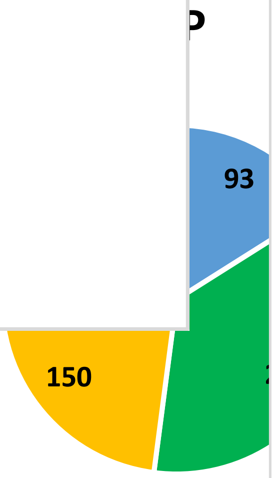
155

28 157

The total weight of the powertrains is 580 kg

- Weight of crankshaft, pistons… - kg
- Weight of head and valve train - kg
- Weight of cylinders block and oil sump - kg
- Weight of auxiliaries, heat exch., … - kg
- Weight of electric motor and inverter -kg
- Weight of the battery pack - kg

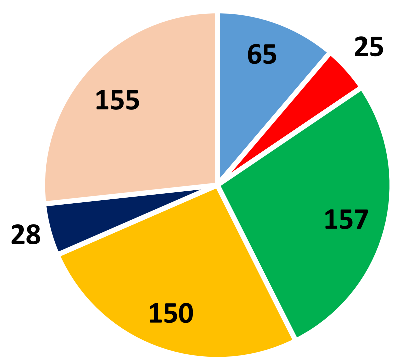




100 kg =15 kWh

Weight of crankshaft, pist

Weight of head and valve



155 kg =23 kWh

Weight of crankshaft, pistons… - kg

Weight of head and valve train - kg

Conclusions (marine application)

- OP (3-cylinder, 6 pistons, 3.7 liters) is the most fuel efficient configuration, enabling up to a 10% saving in cruise conditions, in comparison to the reference 4-stroke. The engine weight reduction (128 kg) enables the installation of 100 kg of electric batteries, corresponding to about 15 kWh, adopting a Lithium Ions technology.
- LS (6-cylinder, V120, 4.2 liters) can be considered a cost effective and lighter alternative to OP: with a single crankshaft, instead of two, and a more flexible layout, further 55 kg may be saved, leading to the installation of a battery pack of 155 kg, corresponding to about 23 kWh, with the same technology. The enhancement of fuel efficiency in comparison to the 4-stroke reference is about 5%, in cruise conditions.
- At this early stage of the project it’s not possible to assess the pollutant emissions, in absolute terms
- In comparison to the reference 4-stroke, at the same load and speed, the proposed 2-strokes are able to generate less soot and NOx. This result is explained by the efficient combustion that can be obtained for each configuration, as well as by the high values of trapped air-fuel ratios at all the operating conditions.
- Thanks to the assistance of the electric motor, the internal combustion engine can be de-rated (lower maximum power), a fundamental advantage for the reduction of pollutant emissions, then for the cost of the after-treatment system

The Range Extender Project (in cooperation with PRIMAVIS)

Why a 2-stroke? How to address the downsides?

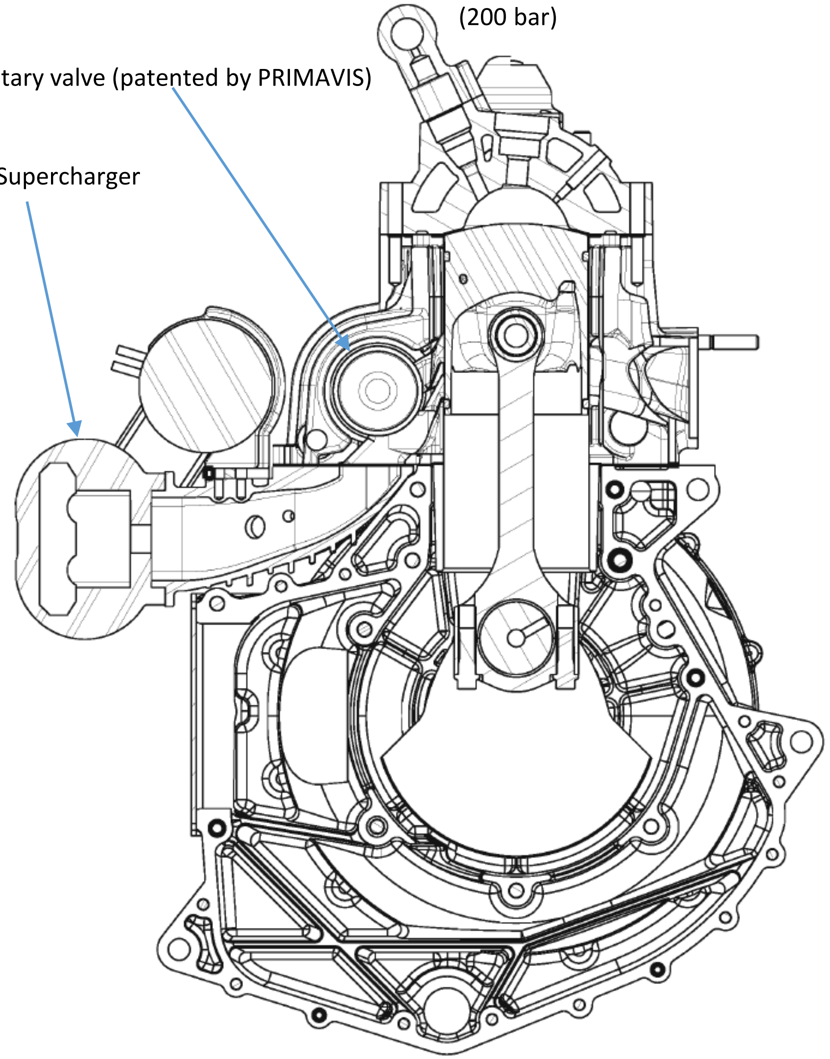
A range extender engine for a small-medium passenger car should:

- deliver no less than 25-30 kW;
- have excellent NVH features;
- be compact and light;
- have reasonable production costs;
- be reliable, efficient and clean

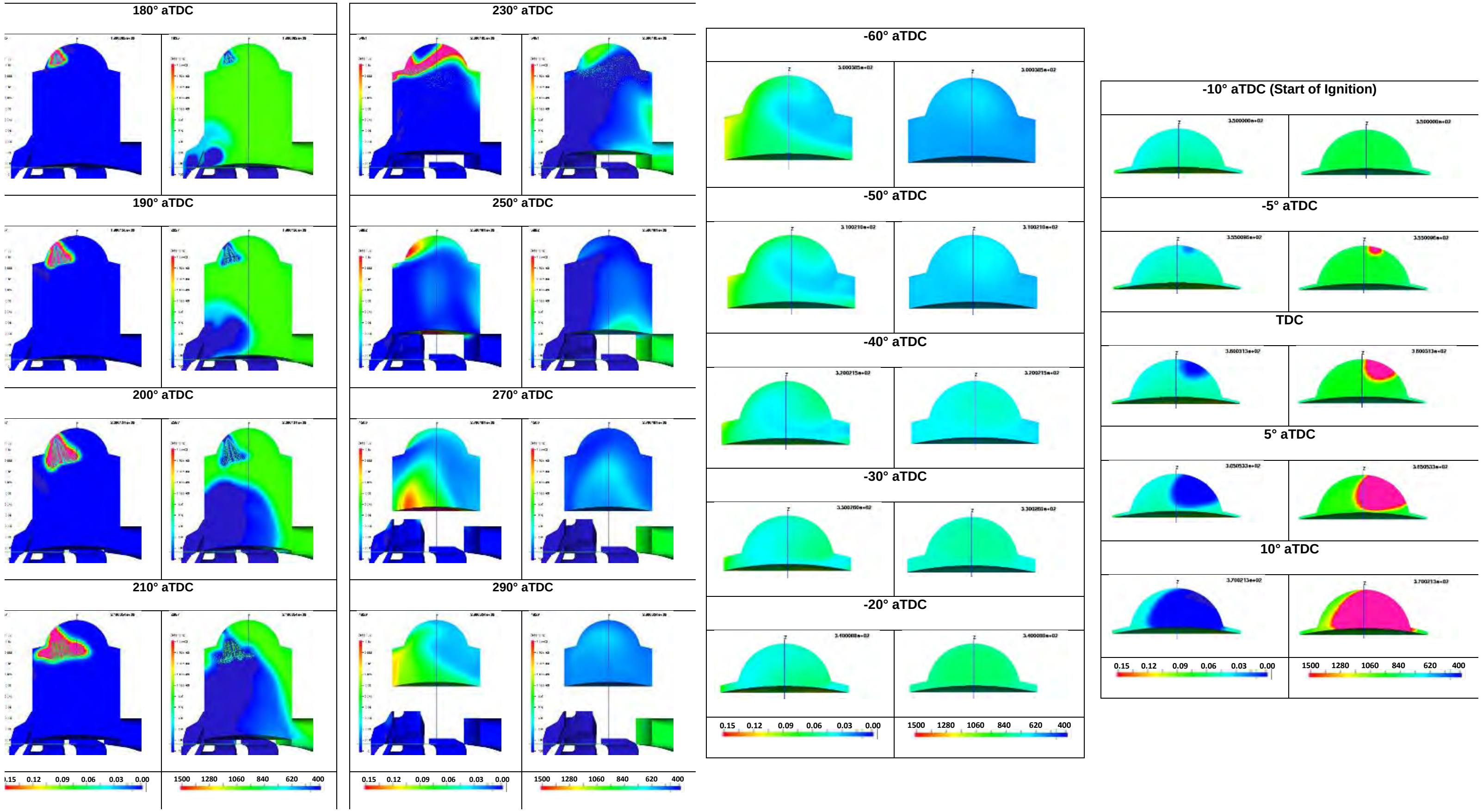
A Spark Ignition 2-stroke engine may possess all these features, adopting the following solutions:

1) Off-the-shelf gasoline direct injection (GDI) system (150-200 bar)
2) External scavenge pump (no crankcase pump → 4-stroke-like oil sump)
3) Optimized scavenging and combustion system
4) Full electronic control of the airflow rate →control of the exhaust gas composition → simple 3-way catalyst

The prototype developed by Primavis and UNIMORE



Scavenging and Combustion simulation at 4500 rpm, full load



Calculated Fuel concentration and temperature

Stages of the project

2012-13: design and building of the first prototype, with piston pump and two sets of reed valves (in cooperation with BRC)

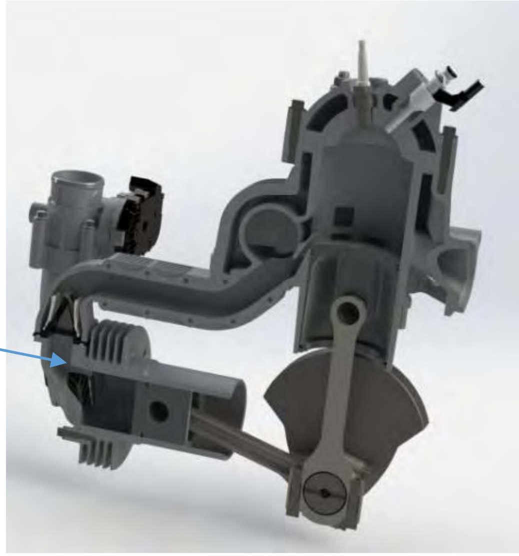
November 2013: first experimental campaign at the BRC laboratories (Cherasco, Italy)

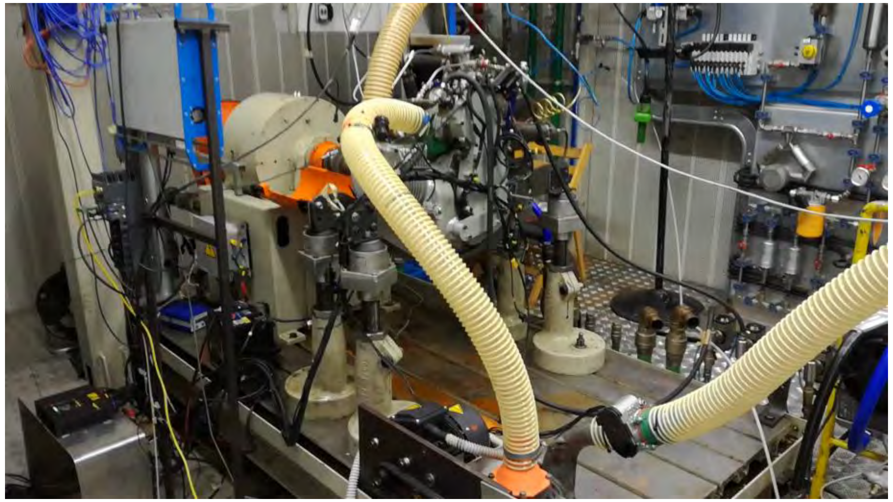
2014-16: Design and building of a second prototype, with new piston pump and new automatic valves

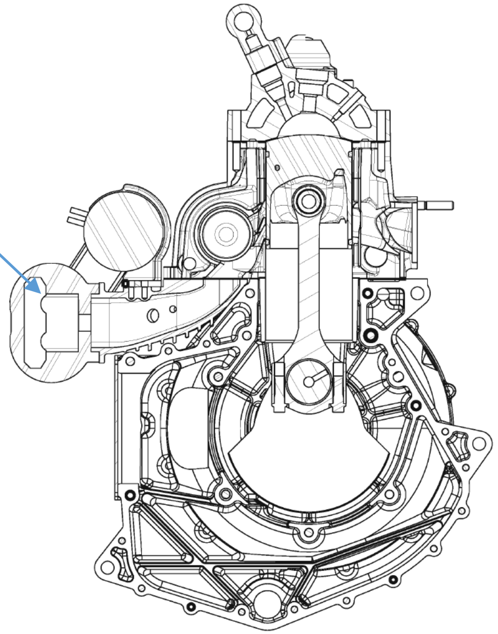
Summer 2016: engine characterization and calibration at the UNIMORE laboratory

2017: Design of a third prototype, replacing the piston pump with an electronically controlled supercharger; new combustion system

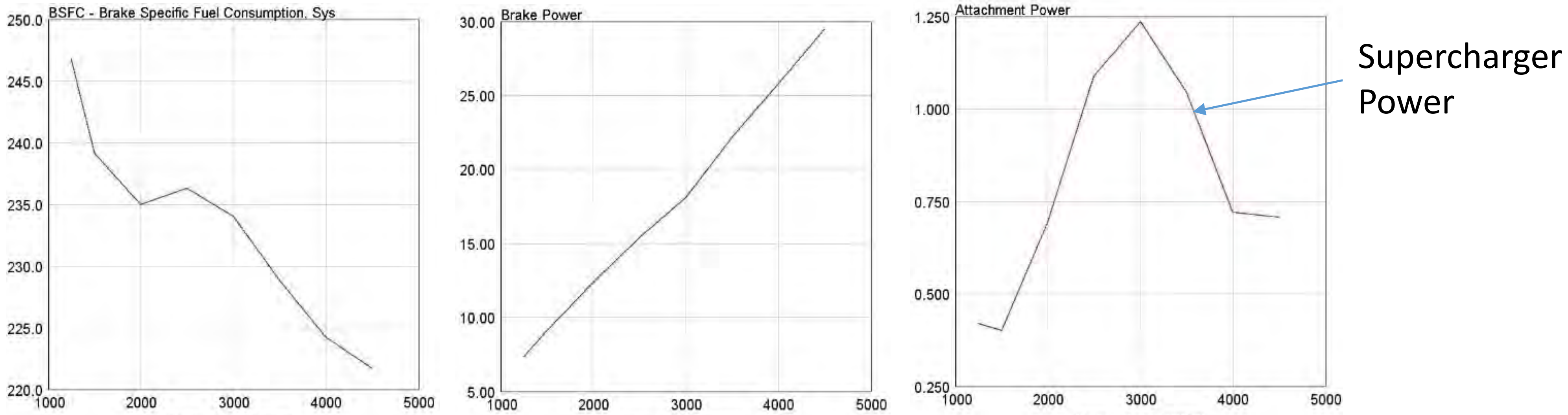
Summer 2017: testing at the UNIMORE laboratory on a modified prototype







Numerical results obtained by experimentally calibrated model



<u>The following advantages are recognized for the proposed 2-S engine, in comparison to a reference 4-S (theoretically developed by the authors, considering the same constraints and goals):</u>

- lower weight (- 35%)
- lower thermal and mechanical loads within the cylinder (-40%, on average), thus NVH advantages;
- lower rejected heat (-18%)
- better brake efficiency for all the power rates (up to +10%, +6% on average)
- wide margins for further combustion improvements, exploiting the potential of direct injection, and the freedom concerning the combustion chamber geometry (GDCI)

<u>The main issues of the 2-Stroke engine, in comparison to a 4-S are:</u>

- lower efficiency of the 3-way catalyst, for the reduction of NOx; it must be compensated by diluting the charge with residuals;
- lower torque: for reaching the same power the engine must run up to 1500 rpm faster, except at peak power;
- complex set-up of the injection parameters, a strong support from CFD-3D simulation is required;
- lubricant blow-by from sump to cylinder

Conclusions

Four different types of innovative 2-stroke combustion systems developed at UNIMORE for:

1. Loop scavenged (valveless) HSDI Diesel engines
2. Opposed piston HSDI Diesel engines
3. Gasoline Direct Injection S.I. engines
4. Dual fuel (Natural Gas-Diesel) Compression Ignition engines (on-going project)

This new generation of 2-stroke engines can be an ideal match for electric motors in many hybrid applications, such as:

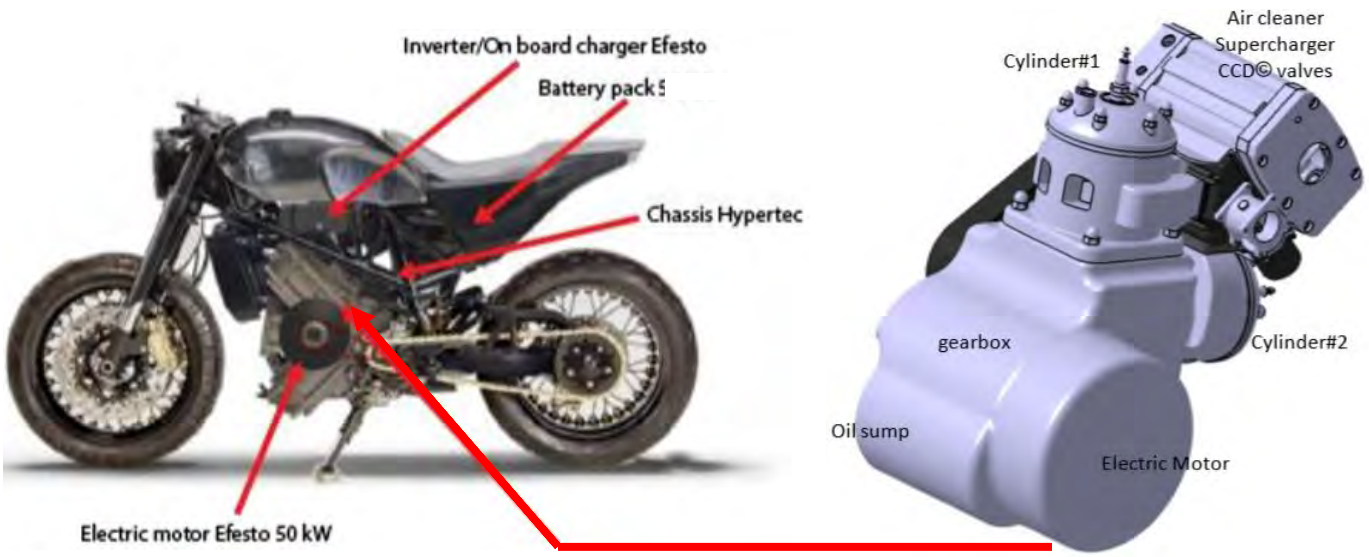
- Range extenders running on gasoline/ethanol for small electric vehicles, aircraft, boats
- hybrid passenger cars, commercial vehicles, off-road vehicles, boats, trucks…
- hybrid high performance motorcycles

Advantages in comparison to conventional 4-strokes:

1) Compactness and weight and cost, compensating the additional charge imposed by hybridization
2) Better capability to operate at clean and efficient combustion modes (HCCI, CAI, GDCI, jet ignition, …)
3) Better fuel efficiency and NVH in most cases

Other Projects on 2-Stroke Hybrid powerplants at Unimore

Current projects, #1: hybrid motorcycle with 2-S GDI engine



The project aims at developing a 2-stroke, GDI engine, as thermal unit of a hybrid motorcycle powertrain
Reference is made to Ducati Monster 1200 R, peak brake power: 117,7 kW, weight 180kg.
The same brake power and the same motorcycle weight should be obtained replacing the original 4-S engine with a hybrid powertrain made up of:

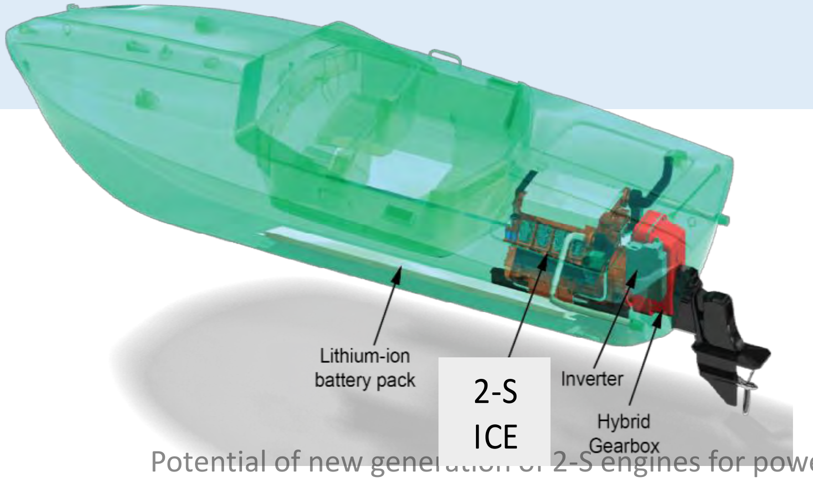
- New 2-S, GDI, 2-cylinder, supercharged ICE (weight 30 kg, top brake power 80 kW@8000rpm), EURO IV compliant
- Electric motor (weight 9 kg, peak power: 50 kW@6000rpm)
- Innovative inverter: 5 kg
- Battery pack: 20 kg, 3 kWh

Current projects, #2: dual fuel (Natural Gas-Diesel) engine for hybrid powertrains (marine application)

Goal: replace a conventional 4-stroke Diesel engine (580 kg, 272 kW@3500 rpm) with a new lightweight 2-stroke running on dual fuel, coupled to an electric motor

Features of the new powertrain:

- Fuel efficient loop scavenged engine, V6, 4.2L, turbocharged, with electronically controlled supercharger;
- NG injection in the transfer ports (semi-direct)
- Less than 20% of power provided by Diesel in any dual fuel operating condition
- Cost effective after-treatment system (no particulate filter required, no SCR)
- Innovative electric motor, fully integrated with the ICE
- pure electric traction capability
- Plug-in battery charge mode
- Capability to run also on Diesel 100% or Natural gas 100% (recovery modes)



Current projects, #3: Opposed Piston Range Extender

The project aims at developing a clean and efficient 2-stroke, opposed piston, single cylinder range extender, rated at 30 kW at 3500 rpm
Each single crankshaft is connected to an electric motor-generator, rated at 15 kW
The offset between the two crankshafts can be set as a function of engine speed and load → effective control of the scavenging and combustion processes
Two different combustion concepts under study: conventional Diesel (already developed with the support of CFD simulations) and Gasoline Compression Ignition (work in process)
Other goals of the project: best bsfc < 210 g/kWh, total weight (including electric motors) < 40 kg, low cost after-treatment system